Renewable and Sustainable Energy Reviews 16 (2012) 5059–5070

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Methane emission by sectors: A comprehensive review of emission sources and mitigation methods

Rafiu O. Yusuf [a], Zainura Z. Noor [a,*], Ahmad H. Abba [a], Mohd Ariffin Abu Hassan [a], Mohd Fadhil Mohd Din [b]

[a] Environmental Engineering Laboratory, Department of Chemical Engineering, Faculty of Chemical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia
[b] Department of Environmental Engineering, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia

ARTICLE INFO

Article history:
Received 28 February 2012
Accepted 6 April 2012
Available online 27 June 2012

Keywords:
Methane
Mitigation
Anthropogenic
Climate change
Global warming
Abatement

ABSTRACT

The global threat caused by increasing surface temperature has led to negative climate changes. One of the greenhouse gases responsible for this global warming is methane. It is emitted naturally and anthropogenically from different sources and its concentration in the atmosphere has assumed alarming proportions. Its devastating consequences on climate change and atmospheric chemistry have made it to be a focus of intense scrutiny and study. The anthropogenic sources of its emissions are generally grouped under three sectors of agriculture, energy and waste. The past emission trends of methane from these sectors are investigated through their sources while mitigation and abatement strategies are suggested. It is observed that the agricultural sector emits the highest amount of methane, followed by the energy and waste sectors, respectively.

Contents

* Corresponding author. Tel.: +60 177 470 315.
E-mail address: zainurazn@utm.my (Z.Z. Noor).

1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2012.04.008

1. Introduction

The emission of greenhouse gases from various sources has resulted in climate change with the attendant increase in global surface temperature [1,2]. Climate change, a resultant effect of greenhouse gas emissions, is a worldwide concern because its continuation is having significant and negative impacts on people, natural resources, and economic conditions around the globe [3–7]. The major greenhouse gases (GHGs) and their relative quantities are water vapour, $H_2O_{(g)}$ (36–70%), carbon dioxide, CO_2 (9–26%), methane, CH_4 (4–9%), and nitrous oxide N_2O (3–7%) plus other trace gases [8]. Of these greenhouse gases, CO_2 and CH_4 have been touted as being responsible for the rise in global surface temperature [9]. The emissions of these gases are caused by both natural and human (anthropogenic) actions.

Methane is only second to carbon dioxide in its contribution to global warming [10]. It is the simplest alkane and is also the principal component of natural gas with bond angles of 109.5° and is formed from the anaerobic decomposition of organic matter in the environment. Methane is a much more powerful greenhouse gas than CO_2 with a high global warming potential (GWP) of 21–25 times more than CO_2 [11–15]. The 100-year GWPs of the greenhouse gases as given in the Second (SAR), Third (TAR) and Fourth (AR4) Assessment Reports are shown in Table 1 [16,17]. Methane is said to be explosive when it is present in the air in concentrations between 5–15% [18,19]. The yearly CH_4 emissions around the world are significantly smaller than CO_2 emissions, and CH_4 concentrations in the atmosphere are about 200 times lower than those of CO_2 [20], but methane accounts for about 20% of global warming [21,22].

It is emitted naturally by wetlands [23,24], termites, wildfires [20], grassland [25], coal beds [26,27] and lakes [28]. The human (anthropogenic) sources of methane emissions include municipal solid wastes (MSW) landfills [29–31], rice paddies [32–34], coal mining [35–37], oil and gas drilling and processing [38,39], cattle ranching [40–42], manure management [43,44], agricultural products [45,46], wastewater treatment plants [47], and rising main sewers [48].

Methane concentration in the atmosphere remained stable for thousands of years before it began to rise in the 19th century (Fig. 1a). In 1750, the concentration of methane in the atmosphere was 676–716 ppb. It rose to 1745 ppb in 1998 and 1800 ppb in 2008 [15,17,49]. The global anthropogenic emissions for methane from all sectors in 2010 were estimated to be 6,875 million metric tons CO_2 equivalent ($MtCO_2eq$) [50,51].

This review examines the emissions of methane from 1990 to 2010 and provides explanation as to the trends observed. Anthropogenic methane emissions pattern from all sources for 2010 are presented in Fig. 1b. The major sources of methane emissions that have been identified are grouped into three main sectors – agriculture, waste, and energy. The sectorial emissions for 2010 are also presented in Fig. 1c while Fig. 1d shows the methane emissions trends from 1990 to 2010. The overall emission pattern indicated growths of 4%, 9%, 15% and 23.5%, respectively, for the years 1995, 2000, 2005 and 2010 over the 1990 emission level. These emissions are projected to grow by a further 32% and 41% respectively by the years 2015 and 2020 [51]. Methane emissions from the agricultural sector increased by 11% by the year 2000 and 24% by the end of 2010. The emissions from the energy sector also increased by 8% in 2000 and 32% by 2010 while the waste sector recorded increases of 4% and 12% by the end of the years 2000 and 2010 respectively. The raw data used in this review were obtained from the report by the US Environmental Protection Agency (EPA).

The patterns of methane emissions from these sectors as well as strategies for the mitigation of these methane emissions from each sector are exhaustively discussed in the following sections.

Table 1
Composition of 100-year GWP of the greenhouse gases.

Gas	SAR	TAR	AR4
CO_2	1	1	1
CH_4	21	23	25
N_2O	310	296	298
HFC-23	11,700	12,000	14,800
HFC-32	650	550	675
HFC-125	2,800	3,400	3,500
HFC-134a	1,300	1,300	1,400
HFC-143a	3,800	4,300	4,470
HFC-152a	140	120	124
HFC-227ea	2,900	3,500	3,200
HFC-236fa	6,300	9,400	9,810
HFC-4310mee	1,300	1,500	1,640
CF_4	6,500	5,700	7,390
C_2F_6	9,200	11,900	12,200
C_4F_{10}	7,000	8,600	8,860
C_6F_{14}	7,400	9,000	9,300
SF_6	23,900	22,200	22,800

2. Agriculture

The average global emissions of methane from the agricultural sector through human (anthropogenic) activities were 3,520 $MtCO_2eq$ which is 52.5% of the total methane emissions from anthropogenic sources [51]. Of these agricultural emissions, those from enteric fermentation (livestock rearing) alone was 53% [6] while emissions from rice cultivation, other agricultural activities and manure management were 18%, 18% and 11%, respectively (Fig. 2a) [51]. Globally, methane emissions from ruminant livestock is 85 Tg of the 550 Tg released annually [52].

Methane emissions from enteric fermentation rose by only 1.5% between 1990 and 2000 but the increase rose to 17% by the end of 2010 [53]. Rice cultivation resulted in a 6% increase in methane emissions from 1990 to 2000 and this shot up to 18% by 2010. Methane emissions from manure management increased by only 1% from 1990 to 2000 but the increase rose to 12% by the year 2010 [53]. Emissions increase from other agricultural sources has remained constant. The trends of methane emissions in the agricultural sector from 1990 to 2010 are illustrated in Fig. 2b.

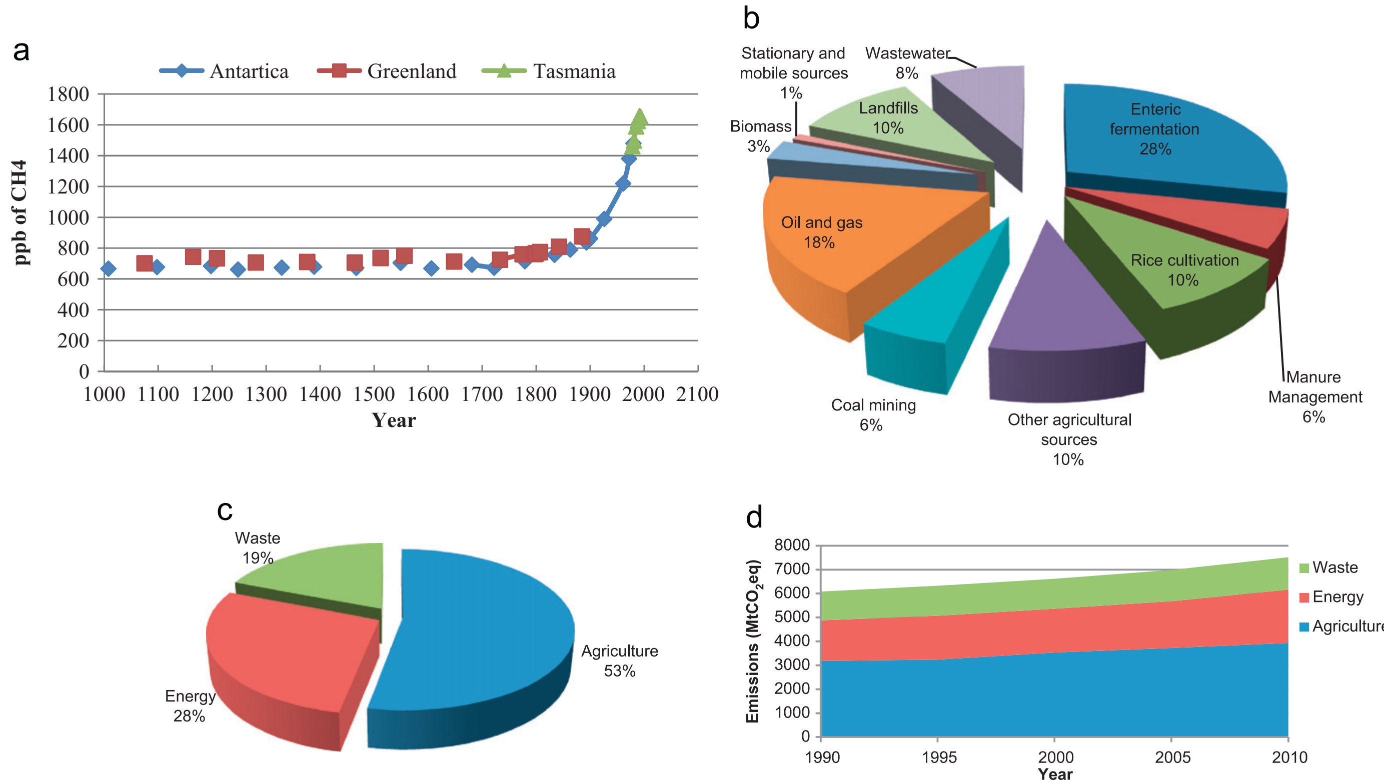

Fig. 1. (a) Methane concentration in the atmosphere. (b) Anthropogenic methane emissions by source in 2010. (c) Anthropogenic methane emission by sectors in 2010. (d) Methane emission trends by sectors from 1990–2010.

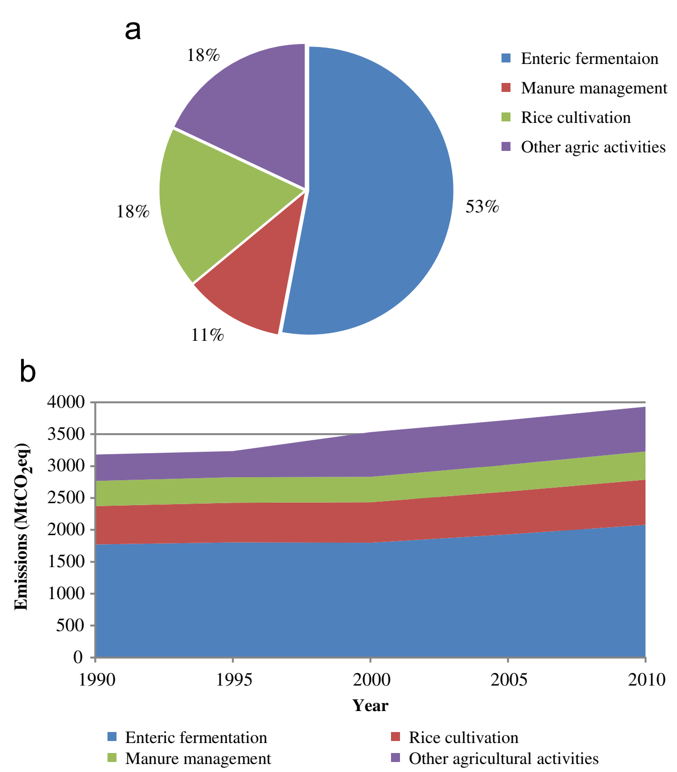

Fig. 2. (a) Methane emissions from agriculture. (b) Methane emissions trend from the agricultural sector (1990–2010).

The main reason for this upward increase in methane emissions is the rising levels of agricultural production with the aim of meeting the demands of rapidly-growing population centres in China, South and East Asia, Latin America, and Africa. Consumption of agricultural products is rising quickly due to increases in both population and income in many areas of these regions. Another factor that will cause increase in the demand for agricultural products is changes in diet preferences, such as an increase in per-capita meat consumption [51]. Overall, global anthropogenic methane emissions from livestock alone is estimated at 35–40% [54], 37% [55] and 25.5% [56].

2.1. Source description

The normal processes of digestion in animals result in methane emissions. Enteric fermentation is a fermentation process in which microbes in the animal's digestive system cause the food to be fermented [40,56,57]. This fermentation takes place in the rumen of ruminant animals like cattle, buffalos, sheep, and goats and result in relatively large methane emissions per unit of feed energy consumed [56]. Methane emissions from enteric fermentation of the domestic livestock contribute significantly to GHG inventories [42,58,59]. Majority of methane emissions in this sector are from domesticated ruminants such as cattle, buffalo, sheep, goats, and camels. Methane emissions by other domesticated non-ruminants such as swine and horses are relatively small [60]. Total emissions are driven by the size of livestock populations and the type of management practices, especially the feed regime used. Also affecting methane emissions are the quantity, quality, and type of feed [51]. The top five countries with respect to global methane emissions from enteric fermentation are China, Brazil, India, the U.S., and Russia [51]. Table 2 shows the world and regional distribution of domesticated ruminant population.

Aerobic decomposition of organic material during flooding of the rice field gradually reduces the oxygen present in the soil and water. This causes the development of anaerobic conditions in the soil and methane is produced through anaerobic decomposition

Table 2
World and regional distribution of domesticated ruminants (10^6).
Source: [61]

Animal type	World	Africa	North America	South America	Asia	Europe	Oceania
Cattle	1347	270	111	315	431	127	38
Buffalo	181	5	–	1	174	0.33	0.0002
Sheep	1078	288	7	73	452	134	113
Goat	862	291	3	21	516	18	1

of soil organic matter by methanogenic bacteria [62,63]. The amount of methane produced depends on water management practices and the quantity of organic material available for decomposition [64]. China and South and East Asian regions are the largest sources of methane emissions from rice cultivation. The single largest contributors in these regions are China, India, Thailand, Indonesia, Vietnam, and Myanmar, which together emit 78% of all emissions from rice cultivation [51]. It is anticipated that yield growth, as opposed to acreage growth, will continue to be the main source of the production growth, with the continued development and adoption of higher-yielding rice varieties in many producing countries [65]. Thailand, Vietnam, and India are projected to dominate global rice exports through the 2005 to 2015 projection period, with an estimated 60% or greater share of the global export market [51]. China is expected to continue to be a significant contributor, but at a lower rate of growth due to decreases in production area [65].

Anaerobic decomposition of manure leads to the production of methane [51]. Three primary factors affect the quantity of methane emitted from manure management operations. These are the type of treatment or storage facility, the ambient climate, and the composition of the manure [43,66]. Storage and treatment of manure in liquid systems such as lagoons, ponds or pits leads to the development of anaerobic conditions which result in methane emissions. Higher ambient temperature and moisture content favour methane production. The composition of manure is directly related to animal types and diets [67]. For example, milk production in dairy cattle is associated with higher feed intake, and therefore higher manure excretion rates than non-dairy cattle. Also, supplemental feeds with higher energy content generally result in a higher potential for methane generation per unit of waste excreted than lower quality pasture diets. In some instances, some higher energy feeds are more digestible than lower quality forages, which can result in less overall waste excreted. Consequently, a combination of all these factors will affect the actual emissions from manure management systems [51]. Methane emissions from manure management are largely from the OECD (Fig. 2d). The top emitting countries are the U.S., Germany, India, China, France, Russia, Turkey, and Brazil [51].

Methane is produced from the open burning of biomass during agricultural activities and from land use change [68,69]. The sources included in this section are savannah burning, agricultural residue burning, and open burning from forest clearing. This category also includes minor amounts of country reported emissions data on methane from agricultural soils [70]. However, biomass burning constitutes the majority of emissions for this source category. Latin America, Africa, and South and East Asia are the largest emitters in this source category. These three regions account for 85% of the methane emissions [51].

2.2. Mitigation measures for the agricultural sector

The mitigation of methane emissions from the agricultural sector is briefly described.

2.2.1. Dietary supplementation

The use of long-chain fatty acids in the diet of the ruminants in the form of processed oilseeds (like canola seed) will reduce methane emissions without affecting diet digestibility [57,71–73]. The use of lipids with ionosphores (such as monensin) in the diet will also cause a reduction in methane emissions [74]. Monensin causes a change in the bacterial species in the rumen resulting in an increased proportion of propionate or could cause a decrease in the numbers of rumen protozoa in the rumen [73]. Linseed fatty acids reduce methane emission but have a negative effect on milk production [75]. Sunflower oil in the diet will reduce methane emission [76]. Incorporating fat in the diet as an energy source lowers the carbohydrate content, which is the substrate for CH_4 formation while the numbers of protozoa in the rumen are also lowered by the fats with many of them physically associated with the methanogens [73]. A reduction in methane emission was noticed when low protein diet was supplemented with amino acids [77].

Effects of short term oral nitroethane administration on methane emissions have been investigated and found to reduce emissions and is an effective anti-methanogenic compound in ruminants fed high forage diets [41]. Combining feed additives like fermented mixed rations of whole–crop rice and rice bran [78] and a mixture of lauric acid, myristic acid, linseed oil and calcium fumarate [79] were found to lower methane emissions. On the other hand a combination of diallyl disulphide, yucca powder, calcium fumarate and linseed oil and another combination of capric acid and caprylic acid were found to have no marked effect on methane emission reduction [80].

2.2.2. Selection of high quality grasses

High quality grasses with high concentration of water-soluble carbohydrates, forage legumes containing secondary metabolites (tannings) and fruits/plants containing saponins have been found to reduce methane emissions [57,81–84].

2.2.3. Increase grain level

Feeding grains and whole plant silages to the animals will reduce methane emission [85,86]. Increasing the level of grain in the diet reduces methane emission because the percentage of the energy consumed that is converted to methane in the rumen is typically reduced to about 3%, from the 6.5% or more that is common for animals fed primarily forages [76]. However, the grain must comprise more than 90% of the diet for any reduction in methane emission to occur [87].

2.2.4. Increasing feed conversion efficiency

Enteric methane emissions could be reduced by improving the efficiency of converting feed to meat and milk [88]. Less enteric methane is generated when the amount of feed it takes to produce animal products is reduced because methane emissions are related to feed intake. This increased efficiency of production can be achieved through animal breeding and improved nutrition [57,81,87].

2.2.5. Increasing animal productivity

Increasing the productivity of individual animals so that fewer animals are required to produce the same amount of product will cause a reduction in methane emission. While the total amount of methane produced per kilogram of milk or meat declines, methane emissions per animal increase [88]. Overall, however, a reduction in methane occurs because animal numbers decrease [89]. Improved feeding and animal genetics in the beef industry can reduce the time cattle are on feed and this will impact on lifetime methane emissions. Furthermore, improving reproductive performance of

cattle can reduce total methane emissions from the herd by reducing the number of replacement heifers required [57,87,90].

2.2.6. *Future options*

Genetic selection of animals, vaccination, probiotics, prebiotics and plant improvement have also been suggested as the most promising future options for methane emissions mitigation [91]. A variety of emission reduction options that can be applied at reasonable costs includes [92] (a) carbon sequestration on extensively used grazing land, (b) reduction of methane emissions from low-input ruminant production and (c) reduction of methane emissions from animal waste through the recovery of energy and waste management improvement.

2.2.7. *Methane emissions mitigation from manure management*

Methane emissions mitigation from manure management dwells much more on slurry systems. There is a direct correlation between methane emission and manure piling height. Lower stacking or piling of the manure leads to lower methane emission [43,93]. Dilution of animal manure before treatment reduces methane emission (Su et al., 2003. Daily flushing and cooling of the slurry will cause a substantial reduction in methane emission [94]. Anaerobic digestion of the manure before outside treatment will cause a reduction in methane emission [67,95]. A reduction in methane emission from the manure of animals fed with low-protein diet that is supplemented with synthetic amino acids has been observed [77]. When compared to broadcasting, application of manure by trail hose and injection reduces methane emission by 0.7 and 3.2% respectively [96].

2.2.8. *Biogas production*

Studies have shown that production of biogas from manure, a renewable form of energy, will reduce methane emissions [3,97–103]. This biogas could be channelled to industries and improve overall eco-efficiency through the creation of industrial symbiosis [104–109]. With an annual biomass production of 220 billion tonnes [110] and studies carried out on household biogas use [111], the importance of this form of energy with respect to strategic and policy shift from fossil fuels cannot be overemphasised [112].

2.3. *Mitigation for rice cultivation*

Methane emission mitigation from rice production can be achieved by the appropriate selection of rice cultivar, water regime and fertilizers and has been shown that rice breeds with heavier total weight emit less methane [113,114]. The incorporation of rice straw compost before transplanting and fresh rice straw three months before transplanting, coupled with intermittent irrigation, brought methane emissions down by 49% and 23% respectively [115]. Drainage of the field during the flowering period and the application of potassium lowered the emission of methane [116,117].

3. Energy

The energy sector is second to agriculture in contribution to global emissions of methane. Methane emissions trend from this sector between 1990 and 2010 is shown in Fig. 3a. Emissions from the oil and gas sector have been on the increase and this trend will continue in view of the expanding economies of the 'BRIC' countries (Brazil, Russia, India, and China). The largest source of methane emissions in the energy sector are fugitive emissions from natural gas and oil systems [51]. They constitute approximately 17% of total man-made sources of global methane emissions and in 2005 totalled approximately 82 billion m^3 (Bcm), (1165 $MtCO_2eq$) [118]. About 28 Bcm (420 $MtCO_2eq$) of methane are released to the atmosphere annually from coal mining activities around the world [119]. Approximately 88% of all

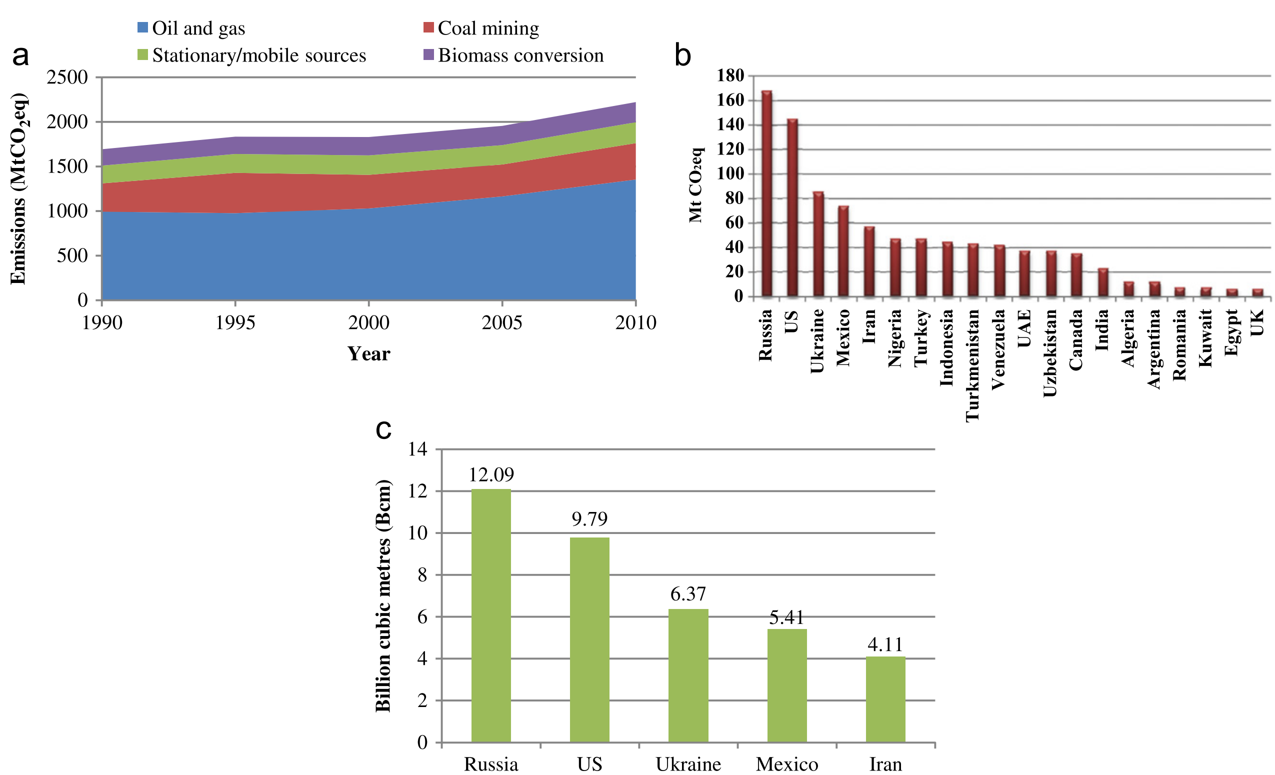

Fig. 3. (a) Methane emissions trends from the energy sector. (b) Global methane emissions from oil and natural gas operations. (c) Top five methane emitting countries from oil and gas.

methane emissions from coal mining originate from only ten countries with the top five, in order of emissions, being China, United States, India, Ukraine and Australia [37]. China is the biggest coal producer in the world with an annual coal output of 2.79 billion tonnes in 2008 [120]. Chinese coal mines emitted up to 18 billion m^3 (270 $MtCO_2eq$) of methane into the atmosphere in 2007 [121]. Decrease in methane emissions from coal mining is envisaged because of a change in sources of energy from coal to natural gas in several areas in Eastern Europe and the Former Soviet Union (FSU) [51].

3.1. Source description

3.1.1. Oil and gas

Methane makes up about 95% of natural gas and is emitted from natural gas production, processing, transmission and distribution. Significant quantities of methane are also emitted from oil production and processing as natural gas is often found in conjunction with petroleum deposits. Methane is a fugitive emission in both oil and natural gas systems, from leaking equipment, system upsets, and deliberate flaring and venting at production fields, processing facilities, transmission lines, storage facilities, and gas distribution lines. Global oil and gas methane emissions increased by 3.6% in 2000 from the 1990 level and by 36% by 2010 (Fig. 3a). The three key factors that have affected the overall trend in global emissions from 1990 to 2010 are the non-EU FSU economic transition, the mild growth in production in parts of the OECD, and the accelerated growth in energy production and demand in all other regions, especially Asia [51].

Fig. 3b shows global oil and gas methane emissions from oil and gas processing for the top twenty emitting countries [118] with the leading emitters of being Russia, US, Ukraine, Mexico and Iran (Fig. 3c). In 1990, the non-EU FSU and OECD countries accounted for 75% of the global methane emissions. The percentage of Russia's contribution to the global emissions will fall from 33% in 1990 to 22% by 2020 [51]. The OECD countries experienced only mild growth of 40% compared to the developing regions because many of these countries have mature natural gas and oil industries, hence oil and gas activities have stagnated. This is in addition to the institution of air quality and safety rules by many OECD countries that have the additional benefit of reducing methane emissions. However, it is likely there will be a continued and growing demand for natural gas in the OECD, which may result in increased emissions in the distribution and transmission sectors.

The Middle East, Latin American, and South and East Asian regions are expected to increase global methane emissions from 22% in 1990 to 33% in 2010 [51]. Electricity production and demand are expected to increase rapidly in the less developed countries of these regions because of populations becoming more urbanized and concentrated with industrial expansion. The resulting increase in energy demands are will drive the rapid growth in fuel production and consumption. Some of the largest oil producing and exporting countries are located in the Middle East and emissions are expected to increase there as a result of increasing world demand for oil.

3.1.2. Coal mining activities

Methane is produced from coal during the process of coalification, where vegetation is converted by geological and biological forces into coal [122,123]. It is then stored within the coal seams and the surrounding rock strata and is liberated when the pressure above or surrounding the coal bed is reduced as a result of natural erosions, faulting, or mining [27,36]. The quantity of gas emitted from mining operations is a function of two primary factors: coal rank and coal depth [51]. Four main sources are responsible for methane emissions from the coal mining. These are underground mines which account for the majority of global methane emissions from coal mining, surface mines which generally emit considerably less methane than underground mines because coal ranks are typically lower and there is less pressure to trap methane in the coal, post-mining operations which refer to the processing, storage, and transportation of the mined coal and abandoned mines where methane emissions from coal mines continue after operations have ceased [50].

There was significant decline in global coal mine methane emissions 1990 to 2000, but increased steadily after 2000 (Fig. 3a). The changes in coal production in China, restructuring of the energy industries in Europe and the non-EU FSU, and industry changes in the U.S are the factors that will affect the expected trend. China's emissions are expected to increase 50% by 2020 due to increased coal production to meet expanding energy needs [120]. Reduced coal production in England and Germany in the 1990s contributed substantially to the reduction in OECD emissions from 1990 to 2000. In Russia and Eastern European coal producing countries, restructuring of the energy industries caused many of the gassiest underground mines to close during the 1990s resulting in a decrease in emissions that has been sustained in the projection years. In the US, decreased emissions from coal mining activities are expected through 2020 because of shift in production from underground to surface coal mines. Reductions due to methane recovery and use of coal bed methane will cause a reduction in methane emissions.

3.1.3. Stationary and mobile sources

Methane is emitted from stationary and mobile combustion as a result of incomplete combustion. However, combustion is a relatively minor contributor to overall methane emission. Methane emissions increased from 199 $MtCO_2eq$ in 1990 to 218 and 235 $MtCO_2eq$ in 2000 and 2010 respectively (Fig. 3a) [51].

3.1.4. Biomass burning

Incomplete biomass combustion leads to the production of methane. The major contributors to methane emissions within this category are municipal waste combustion, charcoal, fuel wood, agricultural residues, and agricultural waste. In the developing world biomass combustion often refers to the combustion of biofuels in small-scale combustion devices for heating, cooking, and lighting purposes. Estimates for this category are highly uncertain and difficult to predict because of the wide variety in the types and conditions under which these fuels are burned. Methane emissions increased from 184 $MtCO_2e$ in 1990 to 206 and 226 $MtCO_2e$ in 2000 and 2010, respectively (Fig. 3a) [51].

3.2. Mitigation options for the energy sector

Methane is emitted in the oil and gas sector during normal operations, system disruptions and routine maintenance. These emissions can be cost-effectively reduced through the upgrade of technologies or equipment and by operational improvement. Some mitigation and abatement options for each unit are briefly discussed. Mitigation options for coal methane are grouped into four.

3.2.1. Oil

The mitigation and abatement options applicable to the oil sector are vapour recovery units, flaring, direct use, and reinjection of gas into oil fields for enhanced oil recovery [51,60,124,125].

3.2.1.1. Install vapour recovery units. Light hydrocarbons vaporise out of solution during the storage of crude oil. These hydrocarbons are then vented into the atmosphere. The vapour recovery unit will capture these vapours for use as fuels or for sale.

3.2.1.2. Flaring in place of venting for both offshore and onshore gas wells. When flaring system is installed, an estimated 98% reduction in fugitive emissions occurs through the burning of vented gas where methane is converted to carbon dioxide. It is more expensive to install a flare in an offshore environment due to technical, environmental, and safety concerns.

3.2.1.3. Direct use of methane. Another abatement option applies primarily to offshore platforms with an estimated reduction efficiency of 90%. This abatement option allows methane to be used for consumption on oil platforms and/or converted to liquefied natural gas.

3.2.1.4. Reinjection of methane. An alternative to flaring or direct use is reinjection of methane where the captured gas from oil field operations is re-injected into the oil production field so as to enhance future oil recovery. This method is estimated to have a reduction efficiency of 95% with a technical lifetime of 15 years.

3.2.1.5. Plunger lift system. A plunger lift can be used to effectively push the fluids out of the well instead of 'venting' gas wells to the atmosphere.

3.2.2. Natural gas

The mitigation and abatement options for each segment of the natural gas system are in the production, processing, transmission and distribution stages [51,124,125].

3.2.2.1. Production abatement options. The production segment of the natural gas sector consists of wells, compressors, dehydrators, pneumatic devices, chemical injection pumps, heaters, meters, pipeline, and central gathering facilities. Available abatement technologies associated with this segment include

a. use catalytic converters in selected well field engines and compressors,
b. replace wet seals with dry seals in centrifugal compressors,
c. direct/enhanced inspection and maintenance at production sites,
d. installation of flash tank separator in glycol dehydration systems,
e. replace high-bleed pneumatic devices with low bleed devices or with instrument air (compressed, dry air) systems, and
f. optimise glycol recirculation rates.

3.2.2.2. Processing abatement options. The processing segment consists of gas plant facilities that encompasses the use of vessels, dehydrators, compressors, acid gas removal (AGR) units, heaters, and pneumatic devices. The technologies for abatement associated with the segment are

a. retrofit fuel gas for reciprocating compressors and blowdown valve,
b. replace wet seals with dry seals in centrifugal compressors,
c. convert gas pneumatic controls to instrument air (compressed, dry air), and
d. Direct inspection and maintenance (DI&M) at gas processing plants.

3.2.2.3. Transmission abatement options. The transmission segment of a natural gas system comprises the transmission pipeline networks, compressor stations, and meter and pressure-regulating stations. The available abatement technologies include:

a. convert gas pneumatic controls to instrument air (compressed, dry air),
b. use pipeline pumpdown techniques to lower gas line pressure before maintenance,
c. DI&M at compressor stations and surface facilities for leak detection,
d. replace wet seals with dry seals in centrifugal compressors, and
e. replace compressor rod packing systems.

3.2.2.4. Distribution abatement options. The distribution segment is made up of the main and service pipeline networks, meter and pressure regulating stations, pneumatic devices, and customer meters. The abatement technologies in this segment include

a. use hot taps in service pipeline connections,
b. DI&M at gate stations,
c. use composite wrap for non-leaking pipeline defects, and
d. use a pipeline pumpdown technique to lower gas line pressure before maintenance.

3.2.3. Coal

When fugitive methane gas from underground coal mines is removed and used in profitable and practical ways, worker safety will be improved, mine productivity will be enhanced, revenues will increase, and greenhouse gas emissions will be reduced [50]. Four abatement options are currently available in the coal mining sector. These are degasification and pipeline injection, enhanced degasification, oxidation of ventilation air methane and flow reversal.

3.2.3.1. Degasification and pipeline injection. High-quality methane is recovered from coal seams when one of the following degasification methods is employed [50,119]: (1) vertical wells (drilled from the surface into the coal seam months or years in advance of mining), (2) gob wells (drilled from the surface into the coal seam just prior to mining), and (3) in-mine boreholes (drilled from inside the mine into the coal seam or the surrounding strata prior to mining). The quality (purity) of the gas that is recovered depends partially on the degasification method employed, and determines how the gas can be used. For example, only high quality gas (typically greater than 95% methane) can be used for injection into natural gas pipelines. Vertical wells and horizontal boreholes into the coal seam tend to recover nearly pure methane (greater than 95% methane). High quality methane can be recovered from very gassy mines, when gob wells are drilled into the gob zone of mined-out coal seams, especially during the first few months of production. This method will cause a 28% emission reduction.

3.2.3.2. Enhanced degasification. In enhanced degasification, methane is recovered in the same way as in degasification, using vertical wells, horizontal boreholes, and gob wells. Furthermore, enrichment technologies such as nitrogen removal units (NRUs) and dehydrators are used primarily to enhance medium-quality gob well gas by removing impurities, thereby allowing larger quantities of methane to be captured and used. It is assumed in this option that well spacing will be tighter for recovery to increase. This process improves recovery efficiency

20% more than the degasification option [126]and causes a 10% emission reduction.

3.2.3.3. Oxidation of ventilation air methane (VAM). Methane emitted from coal mine ventilation air can potentially be utilised by oxidation technologies (both thermal and catalytic). Extremely low methane concentration levels (typically below 1%) render the sale of this gas to a pipeline not economically feasible. However, CO_2 and heat could be generated from an oxidised VAM which in turn may be used directly to heat water or to generate electricity. Application of oxidiser technology to all mine ventilation air with concentrations greater than 0.15% methane will result in the mitigation of about 97% of the methane from the ventilation air. This method will cause a 24% emission reduction.

Medium-to-low quality methane, with concentrations ranging from 35 to 85% can also be used as an energy source in various applications. Potential applications that have been demonstrated in the U.S. and other countries for lower quality coal mine methane (CMM) include [50].

a. Electricity generation with reciprocating engines, gas turbines or steam turbines (the electricity can be used either on-site or can be sold to utilities);
b. As a boiler or dryer fuel in on-site preparation plants or mine vehicle fuel,
c. As a medium-BTU fuel for nearby industrial or institutional facilities; and
d. Cutting-edge applications, such as in fuel cells and chemical processes.

3.2.3.4. Flow reversal. This involves the regenerative heat exchange between a gas and a solid bed of heat exchange medium and can utilise up to 100% of the methane from ventilation shafts. The methane goes into and through the reactor in one direction while temperature is increased until the oxidation of methane is achieved. The hot products of oxidation then give up heat in their movement towards the far side of the bed, and the flow is reversed automatically. The application of heat exchange technologies allows excess heat to be transferred for local heating use, or for power production in gas or steam turbines. It has been proved that the process is capable of sustaining operation with ventilation air at low methane concentrations of 0.1% [126,127].

4. Waste

The waste sector is the third largest contributor to global emissions of non-CO_2 GHGs with the two largest sources being landfilling of solid waste and wastewater treatment. While the sector as a whole accounts for only 15% of all non-CO_2 GHG emissions, landfilling is the fourth largest individual source of emissions (761 $MtCO_2$eq), after agricultural soils (2,001 $MtCO_2$eq), enteric fermentation (1,772 $MtCO_2$eq), and natural gas and oil systems (993 $MtCO_2$eq) [51]. Methane emissions from landfills dropped from 761 $MtCO_2$eq in 1990 to 730 $MtCO_2$eq (4.1%) in 2000 and rose to 761 $MtCO_2$eq in 2010 (Fig. 4a). It is projected to reach 788 and 817 $MtCO_2$eq by 2015 and 2020 respectively [51]. Emissions from wastewater, on the other hand, rose from 446 $MtCO_2$eq in 1990 to 523 $MtCO_2$eq in 2000 (17.3%) and 594 $MtCO_2$eq in 2010, an increase of 33.2% (Fig. 4a). Methane emissions from waste water are projected to be 630 and 665 $MtCO_2$eq by 2015 and 2020 respectively [51].

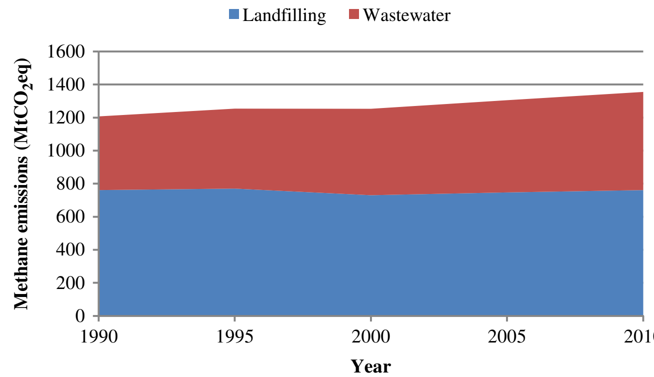

Fig. 4. (a) Total emissions from the waste sector (1990–2010).

4.1. Source description

4.1.1. Solid waste landfill

Methane is produced and emitted from the anaerobic decomposition of organic material in landfills [128–130]. The major drivers of emissions are the amount of organic material deposited in landfills, the extent of anaerobic decomposition, and the level of landfill methane collection and combustion (e.g., energy use or flaring)[131].

The OECD countries emitted nearly 49% of the global methane from the landfilling of solid wastes in 1990. Other regions contributed less than 15% of the methane emissions each for this source category. The 170 $MtCO_2$eq of methane emissions from U.S. were 46% and 23% of the OECD and global total, respectively [53]. Significant shifts in landfills contributions to methane emissions are projected because countries with more steady-state economic growth, and small or declining population growth rates, are expected to experience minimal growth in landfill emissions [132].

The observed decline in emissions from 1990 to 1995 in the OECD are attributed to the collection, flaring and use of landfill methane as well as the non-climate regulatory programs that result in mitigation of air emissions, collection of gas, or closure of facilities [51]. In other regions where diversion of solid waste to managed landfills as a means of improving overall waste management is expected, an increase in methane emissions is envisaged. This will be in addition to the combined effects of rapid economic change, expansive growth policies, and population increase, particularly in the urban centres of developing countries, changing consumption patterns and increases in waste generation [132]. Areas with projected high growth in emissions are Africa at 77% growth, S&E Asia at 34% and Latin America at 52% growth [51].

4.1.2. Wastewater

Methane is emitted during the handling and treatment of municipal and industrial wastewater [133]. Methane emissions from wastewater increased by 17.3% and 33.2% in 2000 and 2010 respectively from the 1990 level of 446 $MtCO_2$eq (Fig. 4a) [51]. The organic material in the wastewater produces methane when it decomposes anaerobically. Most developed countries with centralised aerobic wastewater treatment to handle their municipal wastewater, have low methane emissions are small and incidental. However, in the developing countries, anaerobic systems such as latrines, open sewers, or lagoons with little or no collection and treatment of wastewater are more prevalent. Industrial wastewater can also be treated anaerobically, with significant methane being emitted from those industries with high organic loadings in their wastewater stream, such as food processing and pulp and paper facilities [134].

4.1.3. Source Results

South and East Asia and China accounted for 33% and 24%, respectively, of global methane emissions from wastewater handling in 1990 while Africa, OECD, and Latin America accounted for between 10–12% each [51]. The largest emitters in 1990 were China (21%), India (18%), U.S. (6%), and Indonesia (4%). Wastewater methane emissions in Africa and the Middle East is expected to increase because of population growth, particularly growth associated with countries that rely on less advanced, anaerobic treatment and collection systems such as latrines, septic tanks, open sewers, and lagoons [134]. Most developed countries have an extensive infrastructure to collect and treat urban wastewater, in which the majority of systems rely on aerobic treatment with minimal methane production and thus less effect on the emissions trend [134].

4.2. Abatement options for landfills and wastewater plants

Mitigation and abatement options that are available for landfills and wastewater plants are discussed in the sections.

4.2.1. Emissions reductions from landfills

Vertical wells and horizontal trenches are the methods used as collection systems in most landfills to prevent migration of gas to onsite structures or away from the landfill to adjacent property and to prevent the release of non-methane organic compounds to the atmosphere. Landfill gas (LFG) can be used to produce electricity with engines, turbines, or other technologies, and can be refined and injected into a natural gas pipeline. Using LFG in these ways can yield substantial energy, economic, environmental, air quality, and public health benefits [3,97,99,100,102,110,135–141].

4.2.1.1. Collection and flaring. The presence of methane, if allowed to build up, becomes a public health concern and a safety hazard at landfills. Hence, methane has been removed from large landfills and is combusted through flaring. Gas is collected through vertical wells and a series of horizontal collectors typically installed following the closing of a landfill cell. Vertical wells are the most common type of well, while horizontal collectors are used primarily for deeper landfills and landfill cells that are actively being filled. Once captured, the gas is then channelled through a series of gathering lines to a main collection header. The USEPA recommends that the collection system be designed so that an operator can monitor and adjust the gas flow.

4.2.1.2. Electricity generation. Landfill gas that is extracted using a series of vertical or horizontal wells and a blower (or vacuum) system is collected in a central point, where it can be processed and treated depending on the ultimate use of the gas. From here, the gas can be flared, used to generate electricity, or be pumped to an enduser for process heat.

4.2.1.3. Direct utilisation of gas. Landfill gas can be directly used as fuel to run leachate evaporators and liquid natural gas production. In addition, landfill methane gas can be transported and used in industrial processes, such as boilers, drying operations, kiln operations, and cement and asphalt production. Gas collected from the landfill can be piped directly to local industries where it is used as a replacement or supplementary fuel.

4.2.1.4. Change in waste management practice. Waste management practices can be changed to reduce waste disposal (waste minimisation) at landfills by adding composting and recycling-and-reuse (waste diversion) programs. Incineration is another possible consideration.

4.2.2. Wastewater methane emission abatement

Abatement options for the wastewater sector include the incremental addition of methane mitigation equipment not already included in the initial construction of a municipal wastewater treatment plant, improve existing treatment practices and use anaerobic digesters [47,134,142–145].

4.2.2.1. Improved wastewater treatment practices. These treatment practices for domestic and industrial wastewaters include reduction of the amount of organic waste anaerobically digested. Storing and treating sludge under aerobic conditions is one of the measures. Another option is through improved aeration and/or the scaling back of the use of stagnant settling lagoons. Where the treatment is carried out anaerobically, the methane generated could be captured and used as a source of energy for the heating of the wastewater and sludge digestion tank. Excess methane could be used for electricity generation with flaring being the last resort.

4.2.2.2. Anaerobic digesters. Methane from anaerobic process can be flared or used for cogeneration to reduce methane emissions from biomass or liquid effluents with high organic content.

5. Conclusions

The study has reviewed the emission of methane from three major sectors – agriculture, energy and waste. The dangers posed by continued global warming have been highlighted through the surface temperature profile over the years. The cause of this global warming has been traced to anthropogenic activities through the increased reliance on fossil fuels and forest degradation. Methane has been found to contribute about 20% to this global warming. The review has also shown that the largest sources of anthropogenic methane emissions are agriculture (53%), energy (28%) and waste (19%). Population increase and improved living standards, especially in developing economies, will continue to push these emission values higher in the future. The abatement and mitigation options that have been identified and highlighted will go a long way in reducing these emissions or rechanneling them to other uses and thus safeguard and protect the environment.

References

[1] Calabrò PS. Greenhouse gases emission from municipal waste management: The role of separate collection. Waste Management 2009;29:2178–87.
[2] VijayaVenkataRaman S, Iniyan S, Goic R. A review of climate change, mitigation and adaptation. Renewable and Sustainable Energy Reviews 2012;16(1):878–97.
[3] Abbasi T, Abbasi SA. Biomass energy and the environmental impacts associated with its production and utilization. Renewable and Sustainable Energy Reviews 2010;14(3):919–37.
[4] Bilen K, Ozyurt O, Bakırcı K, Karslı S, Erdogan S, Yılmaz M, et al. Energy production, consumption, and environmental pollution for sustainable development: A case study in Turkey. Renewable and Sustainable Energy Reviews 2008;12(6):1529–61.
[5] Bilgen S, Keleş S, Kaygusuz A, Sarı A, Kaygusuz K. Global warming and renewable energy sources for sustainable development: A case study in Turkey. Renewable and Sustainable Energy Reviews 2008;12(2):372–96.
[6] Naqvi SMK, Sejian V. Global climate change: Role of livestock. Asian Journal of Agricultural Sciences 2011;3(1):19–25.
[7] Yüksel I. Global warming and renewable energy sources for sustainable development in Turkey. Renewable Energy 2008;33:802–12 2008;33:802–12.
[8] Russel R. The greenhouse effect and greenhouse gases. Windows to the Universe: University Corporation for Atmospheric Research; 2007.
[9] Hansen J, Sato M, Kharecha P, Russell G, Lea DW, Siddall M. Climate change and trace gases. Philosophical Transactions of the Royal Society of London, Series A 2007;365:1925–54.
[10] Xiaoli C, Ziyang L, Shimaoka T, Nakayama H, Ying Z, Xiaoyan C, et al. Characteristics of environmental factors and their effects on CH_4 and CO_2

emissions from a closed landfill: An ecological case study of Shanghai. Waste Management 2010;30:446–51.
[11] IPCC. IPCC guidelines for national greenhouse gas inventories. Vol 1–5 Intergovernmental Panel on Climate Change 2006.
[12] Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, et al. Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors. Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2007.
[13] Talyan V, Dahiya RP, Anand S, Sreekrishnan TR. Quantification of methane emission from municipal solid waste disposal in Delhi. Resources, Conservation and Recycling 2007;50:240–59.
[14] Chiu C, Bowling LC, Podest E, Bohn TJ, Lettenmaier DP, Schroeder R, et al. An integrated approach for estimation of methane emissions from wetlands and lakes in high latitude regions. Geophysical Research Abstracts 2009;11 EGU2009-6449-1.
[15] Todd RW, Cole NA, Casey KD, Hagevoort R, Auvermann BW. Methane emissions from southern High Plains dairy wastewater lagoons in the summer. Animal Feed Science and Technology 2011;166–167(0):575–80.
[16] IPCC. Climate Change 2001: The Scientific Basis. In: Houghton YD JT, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Johnson CA, Maskell K, editors. Intergovernmental Panel on Climate Change. United Kingdom: Cambridge; 2001.
[17] IPCC. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: Solomon DQ S, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors. Intergovernmental Panel on Climate Change. United Kingdom: Cambridge; 2007.
[18] Huang Y, He Q. Study on the status of output and utilization of landfill gas in China. Journal of Sichuan University of Science and Engineering (Natural Science Edition) 2008;1:117–20.
[19] Rodríguez R, Lombardía C. Analysis of methane emissions in a tunnel excavated through Carboniferous strata based on underground coal mining experience. Tunnelling and Underground Space Technology 2010;25:456–68.
[20] Mackie KR, Cooper CD. Landfill gas emission prediction using Voronoi diagrams and importance sampling. Environmental Modelling and Software 2009;24:1223–32.
[21] Lelieveld J, Hoor P, Jöckel P, Pozzer A, Hadjinicolaou P, Cammas J-P, et al. Severe ozone air pollution in the Persian Gulf region. Atmospheric Chemistry and Physics 2009;9(4):1393–406.
[22] Wuebbles DJE, Hayhoe K. Atmospheric methane and global change. Earth-Science Reviews 2002;57:177–210.
[23] Agarwal R, Gupta R, Garg JK. A hierarchical model for estimating methane emission from wetlands using MODIS data and ARIMA modeling. Journal of the Indian Society of Remote Sensing 2009;37:473–81.
[24] Li T, Huang Y, Zhang W, Song C. $CH_4MOD_{wetland}$: A biogeophysical model for simulating methane emissions from natural wetlands. Ecological Modelling 2010;221:666–80.
[25] Jones SK, Rees RM, Skiba UM, Ball BC. Greenhouse gas emissions from a managed grassland. Global and Planetary Change 2005;47:201–11.
[26] Cai Y, Liu D, Yao Y, Li J, Qiu Y. Geological controls on prediction of coalbed methane of No. 3 coal seam in Southern Qinshui Basin, North China. International Journal of Coal Geology 2011;88(2–3):101–12.
[27] Ozdemir E. Modeling of coal bed methane (CBM) production and CO_2 sequestration in coal seams. International Journal of Coal Geology 2009;77:145–52.
[28] Makhov GA, Bazhin NM. Methane emission from lakes. Chemosphere 1999;38(6):1453–9.
[29] Chang N-B, Qi C, Islam K, Hossain F. Comparisons between global warming potential and cost–benefit criteria for optimal planning of a municipal solid waste management system. Journal of Cleaner Production 2012;20(1):1–13.
[30] Mendes P, Santos AC, Perna F, Ribau Teixeira M. The balanced scorecard as an integrated model applied to the Portuguese public service: a case study in the waste sector. Journal of Cleaner Production 2012;24(0):20–9.
[31] Raco B, Battaglini R, Lelli M. Gas emission into the atmosphere from controlled landfills: an example from Legoli landfill (Tuscany, Italy). Environmental Science and Pollution Research 2010;17(6):1197–206.
[32] Ma J, Xu H, Cai Z. Effect of fertilization on methane emissions from rice fields. Soils 2010;42(2):153–63.
[33] Yang S-S, Lai C-M, Chang H-L, Chang E-H, Wei C-B. Estimation of methane and nitrous oxide emissions from paddy fields in Taiwan. Renewable Energy 2009;34:1916–22.
[34] Zhang L, Yu D, Shi X, Weindorf DC, Zhao L, Ding W, et al. Simulation of global warming potential (GWP) from rice fields in the Tai-Lake region, China by coupling 1:50,000 soil database with DNDC model. Atmospheric Environment 2009;43:2737–46.
[35] Engle MA, Radke LF, Heffern EL, O'Keefe JMK, Smeltzer CD, Hower JC, et al. Quantifying greenhouse gas emissions from coal fires using airborne and ground-based methods. International Journal of Coal Geology 2011;88(2–3):147–51.
[36] Karacan CÖ, Ruiz FA, Cotè M, Phipps S. Coal mine methane: A review of capture and utilization practices with benefits to mining safety and to greenhouse gas reduction. International Journal of Coal Geology 2011;86(2–3):121–56.
[37] Su S, Han J, Wu J, Li H, Worrall R, Guo H, et al. Fugitive coal mine methane emissions at five mining areas in China. Atmospheric Environment 2011;45(13):2220–32.
[38] Howarth R, Santoro R, Ingraffea A. Methane and the greenhouse-gas footprint of natural gas from shale formations. Climatic Change 2011;106(4):679–90.
[39] Wang T, Geng A, Li X, Wang H, Wang Z, Qiufen L. A prediction model of oil cracked gas resources and Its application in the gas pools of Feixianguan Formation in NE Sichuan Basin, SW China. Journal of Geological Research 2011;2011:11.
[40] Alemu AW, Dijkstra J, Bannink A, France J, Kebreab E. Rumen stoichiometric models and their contribution and challenges in predicting enteric methane production. Animal Feed Science and Technology 2011;166-167(0):761–78.
[41] Brown EG, Anderson RC, Carstens GE, Gutierrez-Bañuelos H, McReynolds JL, Slay LJ, et al. Effects of oral nitroethane administration on enteric methane emissions and ruminal fermentation in cattle. Animal Feed Science and Technology 2011;166-167(0):275–81.
[42] Jones FM, Phillips FA, Naylor T, Mercer NB. Methane emissions from grazing Angus beef cows selected for divergent residual feed intake. Animal Feed Science and Technology 2011;166-167(0):302–7.
[43] Dong H, Zhu Z, Zhou Z, Xin H, Chen Y. Greenhouse gas emissions from swine manure stored at different stack heights. Animal Feed Science and Technology 2011;166–167(0):557–61.
[44] Park KH, Jeon JH, Jeon KH, Kwag JH, Choi DY. Low greenhouse gas emissions during composting of solid swine manure. Animal Feed Science and Technology 2011;166–167(0):550–6.
[45] Bauer A, Bösch P, Friedl A, Amon T. Analysis of methane potentials of steam-exploded wheat straw and estimation of energy yields of combined ethanol and methane production. Journal of Biotechnology 2009;142:50–5.
[46] Wang S, Yang X, Lin X, Hu Y, Luo C, Xu G, et al. Methane emission by plant communities in an alpine meadow on the Qinghai-Tibetan Plateau: a new experimental study of alpine meadows and oat pasture. Biology Letters 2009;5:535–8.
[47] Shahabadi MB, Yerushalmi L, Haghighat F. Estimation of greenhouse gas generation in wastewater treatment plants – Model development and application. Chemosphere 2010;78:1085–92.
[48] Guisasola A, Sharma KR, Keller J, Yuan Z. Development of a model for assessing methane formation in rising main sewers. Water Research 2009;43:2874–84.
[49] Etheridge DM, Steele LP, Francey RJ, Langenfelds RL. Historic CH_4 records from Antarctic and Greenland ice cores, Antarctic firn data, and archived air samples from Cape Grim, Tasmania. In trends: a compendium of data on global change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.; 2002.
[50] GMI. Global Methane Initiative. Underground coal mine methane recovery and use opportunities, 〈http://www.globalmethane.org/documents/coal_fs_eng.pdf〉; 2008 [Accessed 08.02.2012] .
[51] USEPA. Global anthropogenic non-CO_2 greenhouse gas emissions: 1990–2020 Office of Atmospheric Programs, Climate Change Division. Washington D.C: US Environmental Protection Agency; 2006.
[52] McGinn SM, Flesch TK, Harper LA, Beauchemin KA. An approach for measuring methane emissions from whole farms. Journal of Environmental Qualilty 2006;35:14–20.
[53] USEPA. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2009. Washington, DC 20460, USA: U.S. Environmental Protection Agency, EPA 430-R-11-005; 2011.
[54] Aluwong T, Wuyep PA, Allam L. Livestock-environment interactions: Methane emissions from ruminants. African Journal of Biotechnology 2011;10(8):1265–9.
[55] Steinfeld H, Hoffmann I. Livestock, greenhouse gases and global climate change. In: Rowlinson P, Steele, M and Nefzaoui, A, editor. International Conference on Livestock and Global Climate Change 2008, Hammamet, Tunisia; 2008.
[56] Sejian V, Lal R, Lakritz J, Ezeji T. Measurement and prediction of enteric methane emission. International Journal of Biometeorology 2011;55(1): 1–16.
[57] Grainger C, Beauchemin KA. Can enteric methane emissions from ruminants be lowered without lowering their production? Animal Feed Science and Technology 2011;166–167:308–20.
[58] Garcia-Apaza E, Paza ABO, Aranaa I. GHG emissions from enteric fermentation of livestock in Bolivia: values for 1990–2000 and future projections. Australian Journal of Experimental Agriculture 2008;4:255–9.
[59] Huarte A, Cifuentes V, Gratton R, Clausse A. Correlation of methane emissions with cattle population in Argentine Pampas. Atmospheric Environment 2010;44(23):2780–6.
[60] Karakurt I, Aydin G, Aydiner K. Sources and mitigation of methane emissions by sectors: A critical review. Renewable Energy 2012;39(1):40–8.
[61] FAO. FAOSTAT, Agricultural Database of the Food and Agriculture Organization of the United Nations. Italy: Rome, Italy: Food and Agriculture Organisation Rome; 2010.
[62] Nayak DR, A TK, Babu YJ, Datta A, Rao VR BR. Methane emission from a flooded field of Eastern India as influenced by planting date and age of rice (*Oryza sativa* L.) seedlings. Agriculture, Ecosystems and Environment 2006;115:79–87.
[63] Xu S, Jaffe PR, Mauzerall DL. A process-based model for methane emission from flooded rice paddy systems. Ecological Modelling 2007;205:475–91.

[64] Minamikawa K, Sakai N. The effect of water management based on soil redox potential on methane emission from two kinds of paddy soils in Japan. Agriculture, Ecosystems and Environment 2005;107:397–407.
[65] FAPRI. U.S. and World Agricultural Outlook. Food and Agricultural Policy Research Institute, Iowa State University, and University of Missouri-Columbia, Ames, Iowa; 2004.
[66] Johnson KA, Johnson DE. Greenhouse gas inventories from animal agriculture for the United States. International Congress Series 2006;1293:21–8.
[67] Møller HB, Sommer SG, Ahring BK. Biological degradation and greenhouse gas emissions during pre-storage of liquid animal manure. Journal of Environmental Quality 2004;33:27–36.
[68] Dong C, Yang Y, Zhang J, Lu X. Gaseous emissions from the combustion of a waste mixture containing a high concentration of N_2O. Waste Management 2009;29:272–6.
[69] Koppmann R, von Czapiewski K, Reid JS. A review of biomass burning emissions, part I: gaseous emissions of carbon monoxide, methane, volatile organic compounds, and nitrogen containing compounds. Atmospheric Chemistry and Physics Discussions 2005;5:10455–516.
[70] Keppler F, Hamilton JTG, Braß M, Rockmann T. Methane emissions from terrestrial plants under aerobic conditions. Nature 2006;439(7073):187–91.
[71] Beauchemin KA, McGinn SM. Methane emissions from beef cattle: Effects of fumaric acid, essential oil, and canola oil. Journal of Animal Science 2006;84(6):1489–96.
[72] Beauchemin KA, McGinn SM, Martinez TF, McAllister TA. Use of condensed tannin extract from quebracho trees to reduce methane emissions from cattle. Journal of Animal Science 2007;85:1990–6.
[73] Beauchemin KA, McGinn SM, Benchaar C. Holtshausen l. Crushed sunflower, flax, or canola seeds in lactating dairy cow diets: Effects on methane production, rumen fermentation, and milk production. Journal of Dairy Science 2009;92:2118–27.
[74] Takahashi J, Mwenya B, Santoso B, Sar C, Umetsu K, Kishimoto T, et al. Mitigation of methane emission and energy recycling in animal agricultural systems. Asian-Australasian Journal of Animal Science 2005;18(8):1199–208.
[75] Martin C, Rouel J, Jouany JP, Doreau M, Chilliard Y. Methane output and diet digestibility in response to feeding dairy cows crude linseed, extruded linseed, or linseed oil. Journal of Animal Science 2008;86:2642–50.
[76] Beauchemin KA, McGinn SM. Methane emissions from feedlot cattle fed barley or corn diets. Journal of Animal Science 2005;83:653–66.
[77] Osada T, Takada R, Shinzato I. Potential reduction of greenhouse gas emission from swine manure by using a low-protein diet supplemented with synthetic amino acids. Animal Feed Science and Technology 2011;166–167(0):562–74.
[78] Cao Y, Takahashi T, Horiguchi K-i, Yoshida N, Cai Y. Methane emissions from sheep fed fermented or non-fermented total mixed ration containing whole-crop rice and rice bran. Animal Feed Science and Technology 2010;157(1–2):72–8.
[79] van Zijderveld SM, Fonken B, Dijkstra J, Gerrits WJJ, Perdok HB, Fokkink W, et al. Effects of a combination of feed additives on methane production, diet digestibility, and animal performance in lactating dairy cows. Journal of Dairy Science 2011;94(3):1445–54.
[80] van Zijderveld SM, Dijkstra J, Perdok HB, Newbold JR, Gerrits WJJ. Dietary inclusion of diallyl disulfide, yucca powder, calcium fumarate, an extruded linseed product, or medium-chain fatty acids does not affect methane production in lactating dairy cows. Journal of Dairy Science 2011;94(6): 3094–104.
[81] DeRamus HA, Clement TC, Giampola DD. Methane emissions of beef cattle on forages: efficiency of grazing management systems. Journal of Environmental Quality 2003;32:269–77.
[82] Holtshausen L, Chaves AV, Beauchemin KA, McGinn SM, McAllister TA, Odongo NE, et al. Feeding saponin-containing *Yucca schidigera* and *Quillaja saponaria* to decrease enteric methane production in dairy cows. Journal of Dairy Science 2009;92(6):2809–21.
[83] Kasuya H, Takahashi J. Methane emissions from dry cows fed grass or legume silage. Asian-Australasian Journal of Animal Science 2010;23(5): 563–6.
[84] Lascano CE, Cárdenas E. Alternatives for methane emission mitigation in livestock systems. Revista Brasileira de Zootecnia 2010;39:175–82.
[85] McGinn SM, Chung Y-H, Beauchemin KA, Iwaasa AD, Grainger CM. Use of corn distillers' dried grains to reduce enteric methane loss from beef cattle. Canadian Journal of Animal Science 2009;89(3):409–13.
[86] Vellinga TV, Hovin IE. Maize silage for dairy cows: mitigation of methane emissions can be offset by land use change. Nutrient Cycling in Agroecosystems 2011;89:413–26.
[87] Beauchemin KA, McGinn SM. Reducing methane in dairy and beef cattle operations: What is feasible? 2009.
[88] Beukes PC, Gregorini P, Romera AJ, Levy G, Waghorn GC. Improving production efficiency as a strategy to mitigate greenhouse gas emissions on pastoral dairy farms in New Zealand. Agriculture, Ecosystems and Environment 2010;136(3-4):358–65.
[89] Leifeld J, Fuhrer J. Greenhouse gas emissions from Swiss agriculture since 1990: implications for environmental policies to mitigate global warming. Environmental Science and Policy 2005;8:410–7.
[90] Vellinga TV, de Haan MHA, Schils RLM, Evers A, van den Pol–van Dasselaar A. Implementation of GHG mitigation on intensive dairy farms: Farmers' preferences and variation in cost effectiveness. Livestock Science 2011;137(1–3):185–95.
[91] Iqbal MF, Cheng Y-F, Zhu W-Y, Zeshan B. Mitigation of ruminant methane production: current strategies, constraints and future options. World Journal of Microbiology and Biotechnology 2008;24:2747–55.
[92] Steinfeld H, Hoffmann I. Livestock, greenhouse gases and global climate change. In: Rowlinson P, Steele M, Nefzaoui A, editors. International Conference on Livestock and Global Climate Change. Tunisia: Hammamet; 2008 17-20 May, 2008.
[93] Wang J, Duan C, Ji Y, Sun Y. Methane emissions during storage of different treatments from cattle manure in Tianjin. Journal of Environmental Sciences 2010;22(10):1564–9.
[94] Sommer SG, Petersen SO, Møller HB. Algorithms for calculating methane and nitrous oxide emissions from manure management. Nutrient Cycling in Agroecosystems 2004;69:143–54.
[95] Jicong H, Yanhua X, Fengde W, Renjie D. Greenhouse gas emissions from livestock waste: China evaluation. International Congress Series 2006;1293:29–32.
[96] Weiske A, Vabitsch A, Olesen JE, Schelde K, Michel J, Friedrich R, et al. Mitigation of greenhouse gas emissions in European conventional and organic dairy farming. Agriculture, Ecosystems and Environment 2006;112(2–3): 221–32.
[97] Amjid SS, Bilal MQ, Nazir MS, Hussain A. Biogas, renewable energy resource for Pakistan. Renewable and Sustainable Energy Reviews 2011;15(6): 2833–7.
[98] Avcioğlu AO, Türker U. Status and potential of biogas energy from animal wastes in Turkey. Renewable and Sustainable Energy Reviews 2012;16(3): 1557–61.
[99] Dodić SN, Popov SD, Dodić JM, Ranković JA, Zavargo ZZ, Golušin MT. An overview of biomass energy utilization in Vojvodina. Renewable and Sustainable Energy Reviews 2010;14(1):550–3.
[100] Lora ES, Andrade RV. Biomass as energy source in Brazil. Renewable and Sustainable Energy Reviews 2009;13(4):777–88.
[101] Massé DI, Talbot G, Gilbert Y. On farm biogas production: A method to reduce GHG emissions and develop more sustainable livestock operations. Animal Feed Science and Technology 2011;166–167(0):436–45.
[102] Singh J, Gu S. Biomass conversion to energy in India—A critique. Renewable and Sustainable Energy Reviews 2010;14(5):1367–78.
[103] Tock JY, Lai CL, Lee KT, Tan KT, Bhatia S. Banana biomass as potential renewable energy resource: A Malaysian case study. Renewable and Sustainable Energy Reviews 2010;14(2):798–805.
[104] Boons F, Spekkink W, Mouzakitis Y. The dynamics of industrial symbiosis: a proposal for a conceptual framework based upon a comprehensive literature review. Journal of Cleaner Production 2011;19(9–10):905–11.
[105] Costa I, Ferrão P. A case study of industrial symbiosis development using a middle-out approach. Journal of Cleaner Production 2010;18(10-11):984–92.
[106] Costa I, Massard G, Agarwal A. Waste management policies for industrial symbiosis development: case studies in European countries. Journal of Cleaner Production 2010;18(8):815–22.
[107] Geng Y, Tsuyoshi F, Chen X. Evaluation of innovative municipal solid waste management through urban symbiosis: a case study of Kawasaki. Journal of Cleaner Production 2010;18(10-11):993–1000.
[108] Lehtoranta S, Nissinen A, Mattila T, Melanen M. Industrial symbiosis and the policy instruments of sustainable consumption and production. Journal of Cleaner Production 2011;19(16):1865–75.
[109] Taibi E, Gielen D, Bazilian M. The potential for renewable energy in industrial applications. Renewable and Sustainable Energy Reviews 2012;16(1):735–44.
[110] Chandra R, Takeuchi H, Hasegawa T. Methane production from lignocellulosic agricultural crop wastes: A review in context to second generation of biofuel production. Renewable and Sustainable Energy Reviews 2012;16(3):1462–76.
[111] Chen F, Lu S-M, Wang E, Tseng K-T. Renewable energy in Taiwan. Renewable and Sustainable Energy Reviews 2010;14(7):2029–38.
[112] Demirbas MF, Balat M, Balat H. Potential contribution of biomass to the sustainable energy development. Energy Conversion and Management 2009;50(7):1746–60.
[113] Zhao X, He J, Cao J. Study on mitigation strategies of methane emission from rice paddies in the implementation of ecological agriculture. Energy Procedia 2011;5(0):2474–80.
[114] Wassmann R, Hosen Y, Sumfleth K Reducing methane emissions from irrigated rice. 〈http://www.ifpri.org/sites/default/files/publications/focus16_03.pdf〉. Focus 16, Brief 3; 2009 [accessed 15.02.12].
[115] Shin Y-K, Yun S-H, Park M-E, Lee B-L. Mitigation options for methane emission from rice fields in Korea. Ambio: A Journal of the Human Environment 1996;25(4):289–91.
[116] Babu YJ, Nayak DR, Adhya TK. Potassium application reduces methane emission from a flooded field planted to rice. Biology and Fertility of Soils 2006;42:532–41.
[117] Towprayoon S, Smakgahn K, Poonkaew S. Mitigation of methane and nitrous oxide emissions from drained irrigated rice fields. Chemosphere 2005;59:1547–56.
[118] Schlagenhauf M, Waltzer S, Jacobs RL, Freitas CJ. Methane from oil and gas operations—a source of free fuel for on-site generation? Cogeneration & On-Site Power Production Magazine 〈http://wwwcosppcom/articles/print/volume-8/issue-6/features/methane-from-oil-and-gas-operations-a-source-of-free-fuel-for-on-site-generationhtml〉; 2007 [Accessed 15.01.12].
[119] Franklin P. Methane from coal mines presents opportunity to recover energy and generate revenues. Coalbed methane outreach program. US Environmental Protection Agency; 2009.

[120] Wang YH. Coal demand and coal industry development in China. In: 5th meeting of the Australia–China bilateral dialogue on resources cooperation. Sydney, Australia; 3 December 2009.
[121] Su S, Adhikary D, Worrall R, Gabeva D. Study on coal mine methane resources and potential project development CSIRO exploration and mining report P2009/423; 2009.
[122] Krzysztof W. Harnessing methane emissions from coal mining. Process Safety and Environmental Protection 2008;86(5):315–20.
[123] Tan Z, Wang S, Ma L. Current Status and Prospect of Development and Utilization of Coal Mine Methane in China. Energy Procedia 2011;5(0):1874–7.
[124] Fernandez R, Robinson DR Projects that achieve large methane emissions reductions in oil and gas operations. Oil and gas methane emissions reduction workshop. Tomsk, Russia; 14–16 September 2005.
[125] Robinson DR, Fernandez R, Kantamaneni R. Methane emissions mitigation options in the global oil and natural gas industries. 3rd international methane and nitrous oxide mitigation conference; 2003.
[126] Schultz K. Coal mine-ventilation air methane mitigation: technologies to harnass an energy and environmental resource. Energeia 2003;14(5):1–3.
[127] Somers JM, Schultz HL. Coal mine methane ventilation air emissions: new mitigation technologies. 9th Congress on Ventilation Air Methane. India 2009.
[128] Abushammala MFM, Ahmad Basri NE, Basri H, El-Shafie AH, Kadhum AAH. Regional landfills methane emission inventory in Malaysia. Waste Management & Research 2010.
[129] Bicheldey TK, Latushkina EN. Biogass emission prognosis at the landfills. International Journal of Environmental Science and Technology 2010;7(4): 623–8.
[130] Wangyao K, Yamada M, Endo K, Ishigaki T, Naruoka T, Towprayoon S, et al. Methane generation rate constant in tropical landfill. Journal of Sustainable Energy and Environment 2010;1:181–4.
[131] Jha AK, Sharma C, Singh N, Ramesh R, Purvaja R, Gupta PK. Greenhouse gas emissions from municipal solid waste management in Indian mega-cities: a case study of Chennai landfill sites. Chemosphere 2008;71:750–8.
[132] Franchetti MJ. Solid waste analysis and minimization: a systems approach. New York: McGraw-Hill Company, Inc; 2009.
[133] Shirai Y, Wakisaka M, Yacob S, Hassan MA, Suzuki S. Reduction of methane released from palm oil mill lagoon in malaysia and its countermeasures. Mitigation and Adaptation Strategies for Global Change 2003;8:237–52.
[134] El-Fadel M, Massoud M. Methane emissions from wastewater management. Environmental Pollution 2001;114:177–85.
[135] Asif M. Sustainable energy options for Pakistan. Renewable and Sustainable Energy Reviews 2009;13:903–9.
[136] Chen Y, Yang G, Sweeney S, Feng Y. Household biogas use in rural China: A study of opportunities and constraints. Renewable and Sustainable Energy Reviews 2010;14(1):545–9.
[137] Mekhilef S, Saidur R, Safari A. Mustaffa WESB. Biomass energy in Malaysia: Current state and prospects. Renewable and Sustainable Energy Reviews 2011;15(7):3360–70.
[138] Singh RP, Tyagi VV, Allen T, Ibrahim MH, Kothari R. An overview for exploring the possibilities of energy generation from municipal solid waste (MSW) in Indian scenario. Renewable and Sustainable Energy Reviews 2011;15(9):4797–808.
[139] Gewald D, Siokos K, Karellas S, Spliethoff H. Waste heat recovery from a landfill gas-fired power plant. Renewable and Sustainable Energy Reviews 2012;16(4):1779–89.
[140] Panwar NL, Kothari R, Tyagi VV. Thermo chemical conversion of biomass—Eco friendly energy routes. Renewable and Sustainable Energy Reviews 2012;16(4):1801–16.
[141] Zheng YH, Li ZF, Feng SF, Lucas M, Wu GL, Li Y, et al. Biomass energy utilization in rural areas may contribute to alleviating energy crisis and global warming: A case study in a typical agro-village of Shandong, China. Renewable and Sustainable Energy Reviews 2010;14(9):3132–9.
[142] Fine P, Hadas E. Options to reduce greenhouse gas emissions during wastewater treatment for agricultural use. Science of The Total Environment 2012;416(0):289–99.
[143] Flores-Alsina X, Corominas L, Snip L, Vanrolleghem PA. Including greenhouse gas emissions during benchmarking of wastewater treatment plant control strategies. Water Research 2011;45(16):4700–10.
[144] Pan T, Zhu X-D, Ye Y-P. Estimate of life-cycle greenhouse gas emissions from a vertical subsurface flow constructed wetland and conventional wastewater treatment plants: A case study in China. Ecological Engineering 2011;37(2):248–54.
[145] Préndez M, Lara-González S. Application of strategies for sanitation management in wastewater treatment plants in order to control/reduce greenhouse gas emissions. Journal of Environmental Management 2008;88(4):658–64.